APPENDIX H

Partition Coefficients For Strontium

Appendix H

Partition Coefficients For Strontium

H.1.0 Background

Two simplifying assumptions underlying the selection of strontium K_d values included in the look-up table were made. These assumptions are that the adsorption of strontium adsorption occurs by cation exchange and follows a linear isotherm. These assumptions appear to be reasonable for a wide range of environmental conditions. However, these simplifying assumptions are compromised in systems with strontium concentrations greater than about 10^{-4} M, humic substance concentrations greater than about 5 mg/l, ionic strengths greater than about 0.1 M, and pH levels greater than approximately 12.

Based on these assumptions and limitations, strontium K_d values and some important ancillary parameters that influence cation exchange were collected from the literature and tabulated in Section H.3. The tabulated data were from studies that reported K_d values (not percent adsorbed or Freundlich or Langmuir constants) and were conducted in systems consisting of

- Natural soils (as opposed to pure mineral phases)
- Low ionic strength (< 0.1 M)
- pH values between 4 and 10
- Strontium concentrations less than 10^{-4} M
- Low humic material concentrations (<5 mg/L)
- No organic chelates (such as EDTA)

The ancillary parameters included clay content, pH, CEC, surface area, solution calcium concentrations, and solution strontium concentrations. The table in Section H.3 describes 63 strontium K_d values. Strontium K_d values for soils as well as pure mineral phases are tabulated in Section H.4. This table contains 166 entries, but was not used to provide guidance regarding the selection of K_d values to be included in the look-up table.

Statistical analysis were conducted with the data collected from the literature. These analyses were used as guidance for selecting appropriate K_d values for the look-up table. The K_d values used in the look-up tables could not be based entirely on statistical consideration because the statistical analysis results were occasionally nonsensible. For instance, negative K_d values were predicted by 1 regression analysis. Thus, the K_d values included in the look-up table were not selected purely by objective reasoning. Instead, the statistical analysis was used as a tool to provide guidance for the selection of the approximate range of values to use and to identify meaningful trends between the strontium K_d values and the soil parameters.

The descriptive statistics of the strontium K_d data set for soil data only (entire data set presented in Section H.3) is presented in Table H.1. The 63 strontium K_d values in this data set ranged from

1.6 ml/g for a measurement made on a sandy soil dominated by quartz (Lieser *et al.*, 1986) to 10,200 ml/g for a measurement made on a tuff[1] soil collected at Yucca Mountain, Nevada (Sample YM-38; Vine *et al.*, 1980). The average strontium K_d value was 355 ± 184 ml/g. The median[2] strontium K_d value was 15.0 ml/g. This is perhaps the single central estimate of a strontium K_d value for this data set.

Table H.1. Descriptive statistics of strontium K_d data set for soils.

	Sr K_d (ml/g)	Clay Content (wt.%)	pH	CEC (meq/100 g)	Surface Area (m²/g)	Ca (mg/l)
Mean	355	7.1	6.8	4.97	1.4	56
Standard Error	183	1.1	0.21	1.21	0	23
Median	15	5	6.7	0.9	1.4	0
Mode	21	5	6.2	2	1.4	0
Standard Deviation	1,458	7.85	1.35	9.66	0.00	134
Kurtosis	34	10.7	-0.5	11.6	-3	3.4
Minimum	1.6	0.5	3.6	0.05	1.4	0.00
Maximum	10,200	42.4	9.2	54	1.4	400
Number of Observations	63	48	42	63	7.00	32

[1] Tuff is a general name applied to material dominated by pyroclastic rocks composed of particles fragmented and ejected during volcanic eruptions.

[2] The median is that value for which 50 percent of the observations, when arranged in order of magnitude, lie on each side.

H.2.0 Approach and Regression Models

H.2.1 Correlations with Strontium K_d Values

A matrix of the correlation coefficients of the strontium K_d values and soil parameters are presented in Table H.2. The correlation coefficients significant at or less than the 5 percent level of probability ($P \leq 0.05$) are identified in Table H.2. The highest correlation coefficient with strontium K_d values was with CEC ($r = 0.84$). Also significant are the correlation coefficients between strontium K_d values and clay content ($r = 0.82$) and CEC and clay content ($r = 0.91$) (Table H.2).

H.2.2 Strontium K_d Values as a Function of CEC and pH

The CEC and strontium K_d data are presented in Figure H.1. It should be noted that a logarithmic scale was used for the y-axis to assist in the visualization of the data and is not meant to suggest any particular model. A great deal of scatter exists in this data, especially in the lower CEC range where more data exist. For example, between the narrow CEC range of 5.5 to 6.0 meq/100 g, 9 strontium K_d values are reported (Keren and O'Connor, 1983; McHenry, 1958; Serne *et al.*, 1993). The strontium K_d values range from 3 ml/g for a surface noncalcareous sandy loam collected from New Mexico (Keren and O'Connor, 1983) to 70 ml/g for a carbonate surface soil collected from Washington (McHenry, 1958). Thus, over an order of magnitude variability in strontium K_d values may be expected at a given CEC level.

Table H.2. Correlation coefficients (r) of the strontium K_d data set for soils.

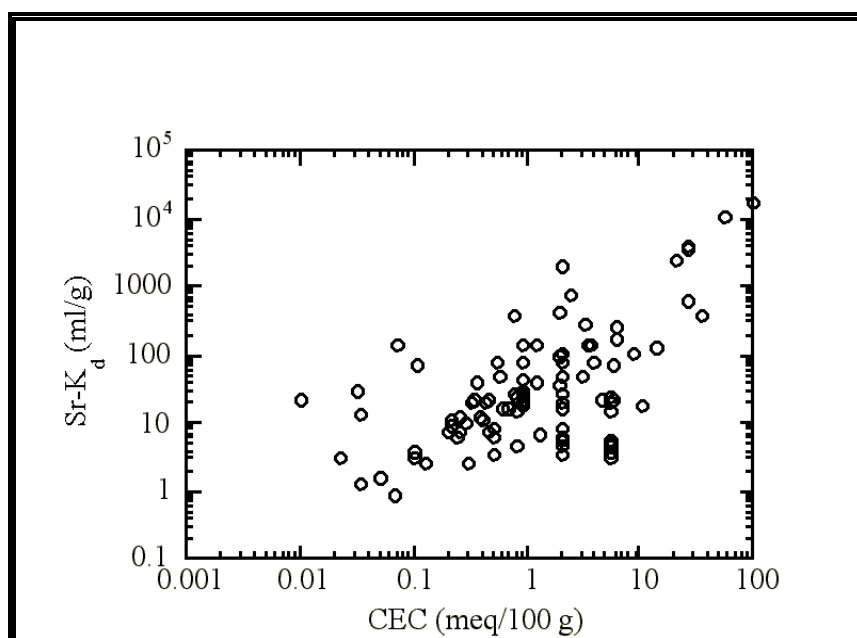|	Strontium K_d	Clay Content	pH	CEC	Surface Area	Ca Conc.
Strontium K_d	1.00					
Clay Content	0.82[1]	1.00				
pH	0.28	0.03	1.00			
CEC	0.84[1]	0.91[1]	0.28[1]	1.00		
Surface Area	0.00	-1.00	0.00	1.00[1]	1.00	
Ca Conc.	-0.17	0.00	-0.20	0.03	---	1.00
[1] Correlation coefficients significant at or less than the 5% level of probability ($P \leq 0.05$).						

Figure H.1. Relation between strontium K_d values and
CEC in soils.

Another important issue regarding this data set is that 83 percent of the observations exists at CEC values less than 15 meq/100 g. The few K_d values associated with CEC values greater than 15 meq/100 g may have had a disproportionally large influence on the regression equation calculation (Neter and Wasserman, 1974). Consequently, estimates of strontium K_d values using these data for low CEC soils, such as sandy aquifers, may be especially inaccurate.

The regression equation for the data in Figure H.1 is presented as Equation 1 in Table H.3. Also presented in Table H.3 are the 95 percent confidence limits of the calculated regression coefficients, the y-intercepts, and slopes. These coefficients, when used to calculate K_d values, suggest a K_d range at a given CEC by slightly over an order of magnitude. The lower 95 percent confidence limit coefficients can provide guidance in selecting lower (or conservative) K_d values.

The large negative intercept in Equation 1 compromises its value for predicting strontium K_d values in low CEC soils, a potentially critical region of the data, because many aquifers matrix have low CEC values. At CEC values less than 2.2 meq/100 g, Equation 1 yields negative strontium K_d values, which are clearly unrealistic.[1] To provide a better estimate of strontium K_d

---

[1] A negative K_d value is physically possible and is indicative of the phenomena referred to as anion exclusion or negative adsorption. It is typically and commonly associated with anions being

values at low CEC values, 2 approaches were evaluated. First, the data in Figure H.1 was reanalyzed such that the intercept of the regression equation was set to zero, *i.e.*, the regression equation was forced through the origin. The statistics of the resulting regression analysis are presented as Equation 2 in Table H.3. The coefficient of determination (R^2) for Equation 2 slightly decreased compared to Equation 1 to 0.67 and remained highly significant ($F= 2x10^{-16}$). However, the large value for the slope resulted in unrealistically high strontium K_d values. For example at 1 meq/100 g, Equation 2 yields a strontium K_d value of 114 ml/g, which is much greater than the actual data presented in Figure H.1.

The second approach to improving the prediction of strontium K_d values at low CEC was to limit the data included in the regression analysis to those with CEC less than 15 meq/100 g. These data are redrawn in Figure H.2. The accompanying regression statistics with the y-intercept calculated and forced through the origin are presented in Table H.3 as Equations 3 and 4, respectively. The regression equations are markedly different from there respective equations describing the entire data set, Equations 1 and 2. Not surprisingly, the equations calculate strontium K_d more similar to those in this reduced data set. Although the coefficients of determination for Equations 3 and 4 decreased compared to those of Equations 1 and 2, they likely represent these low CEC data more accurately.

Including both CEC and pH as independent variables further improved the predictive capability of the equation for the full data set as well as the data set for soils with CEC less than 15 meq/100 g (Equations 5 and 6 in Table H.3). Multiple regression analyses with additional parameters did not significantly improve the model (results not presented).

H.2.3 Strontium K_d Values as a Function of Clay Content and pH

Because CEC data are not always available to contaminant transport modelers, an attempt was made to use independent variables in the regression analysis that are more commonly available to modelers. Multiple regression analysis was conducted using clay content and pH as independent variables to predict CEC (Equations 7 and 8 in Table H.3) and strontium K_d values (Equations 9 and 10 in Table H.3; Figures H.3 and H.4).   The values of pH and clay content were highly correlated to soil CEC for the entire data set ($R^2 = 0.86$) and for those data limited to CEC less than 15 meq/100 g ($R^2 = 0.57$). Thus, it is not surprising that clay content and pH were correlated to strontium K_d values for both the entire data set and for those associated with CEC less than 15 meq/100 g.

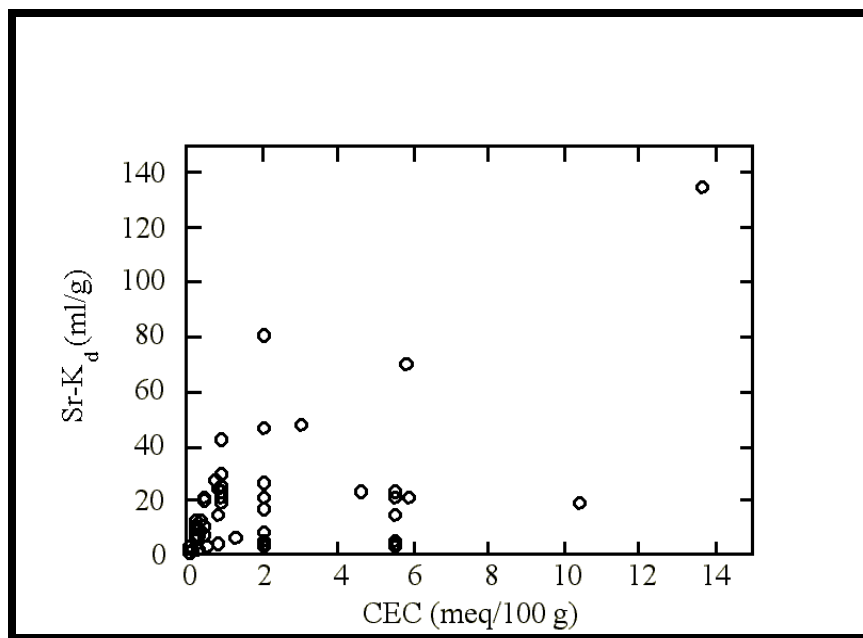repelled by the negative charge of permanently charged minerals.

Figure H.2. Relation between strontium K_d values for soils with CEC values less than 15 meq/100 g.
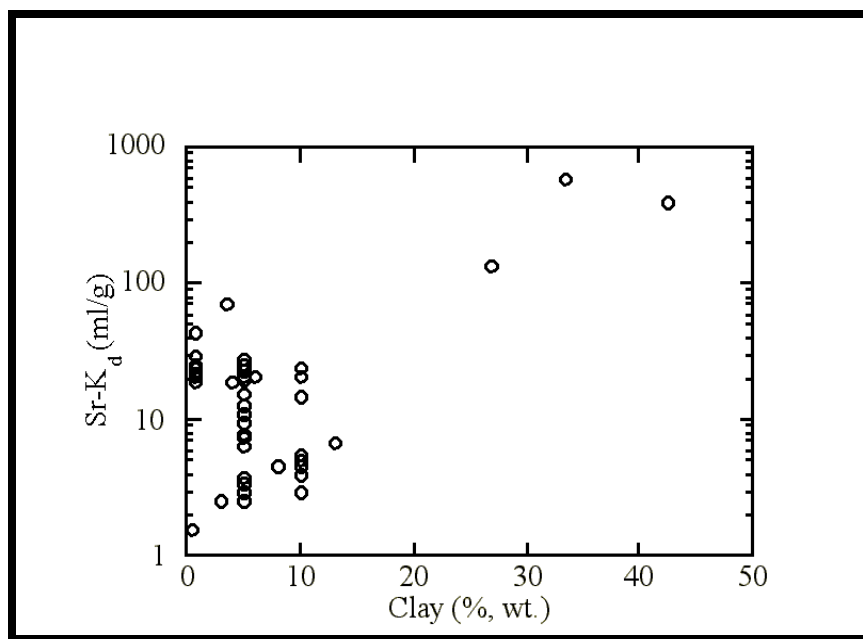

Figure H.3. Relation between strontium K_d values and soil clay contents.

Table H.3. Simple and multiple regression analysis results involving strontium K_d values, cation exchange capacity (CEC; meq/100 g), pH, and clay content (percent).

#	Equation	n^2	Data Range [3]	Intercept Lower	Intercept Upper	Slope First Independent Parameter Lower	Slope First Independent Parameter Upper	Slope Second Independent Parameter Lower	Slope Second Independent Parameter Upper	R^2 [4]	F Value[5]
1	$K_d = -272 + 126(CEC)$	63	All	-501	-43	105	147	---	---	0.70	1×10^{-17}
2	$K_d = 114(CEC)$	63	All	---	---	95	134	---	---	0.67	2×10^{-16}
3	$K_d = 10.0 + 4.05(CEC)$	57	CEC<15	3.32	16.6	2.13	5.96	---	---	0.25	9×10^{-5}
4	$K_d = 5.85(CEC)$	57	CEC<15	---	---	4.25	7.44	---	---	0.12	7×10^{-3}
5	$K_d = -42 + 14(CEC) + 2.33(pH)$	27	All	-176	91	11.3	18.3	-17.7	22.4	0.77	3×10^{-8}
6	$K_d = 3.53(CEC) + 1.67(pH)$	25	CEC<15	---	---	0.62	6.46	-0.50	3.85	0.34	9×10^{-3}
7	$CEC = -4.45 + 0.70(clay) + 0.60(pH)$	27	All	-10.6	1.67	0.59	0.82	-0.30	1.50	0.86	4×10^{-11}
8	$CEC = 0.40(clay) + 0.19(pH)$	25	CEC<15	---	---	0.24	0.56	-0.01	0.40	0.55	1×10^{-4}
9	$K_d = -108 + 10.5(clay) + 11.2(pH)$	27	All	-270	53.3	7.32	13.6	-12.5	34.9	0.67	2×10^{-6}
10	$Kd = 3.54(clay) + 1.67(pH)$	25	CEC<15	---	---	0.62	6.46	-0.50	3.85	0.34	9×10^{-3}
11	$Clay = 3.36 + 1.12(CEC)$	48	All	2.30	4.41	0.97	1.26	---	---	0.84	1×10^{-19}
12	$Clay = 1.34(CEC)$	48	All	---	---	1.16	1.51	---	---	0.69	2×10^{-13}

[1] The 95% confidence limits provides the range within which one can be 95% confident that the statistical parameter exist.
[2] The number of observations in the data set.
[3] All available observations were included in regression analysis except when noted.
[4] R^2 is the coefficient of determination and represents the proportion of the total treatment sum of squares accounted for by regression (1.00 is a perfect match between the regression equation and the data set).
[5] The F factor is a measure of the statistical significance of the regression analysis. The acceptable level of significance is not standardize and varies with the use of the data and the discipline. Frequently, a regression analysis with a F value of less than 0.05 is considered to describe a significant relationship.
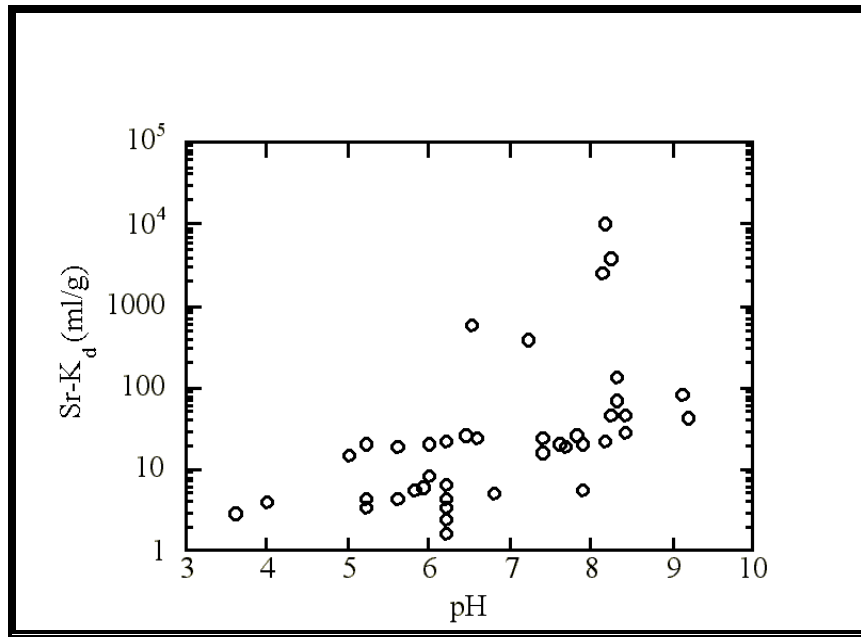
Figure H.4.   Relation between strontium K_d values and soil pH.

H.2.4 Approach

Two strontium K_d look up tables were created. The first table requires knowledge of the CEC and pH of the system in order to select the appropriate strontium K_d value (Table H.4). The second table requires knowledge of the clay content and pH to select the appropriate strontium K_d value (Table H.5).

A full factorial table was created that included 3 pH categories and 3 CEC categories. This resulted in 9 cells. Each cell contained a range for the estimated minimum- and maximum K_d values. A 2 step process was used in selecting the appropriate K_d values for each cell. For the first step, the appropriate equations in Table H.3 were used to calculate K_d values. The lower and upper 95 percent confidence limit coefficients were used to provide guidance regarding the minimum and maximum K_d values. For the 2 lowest CEC categories, Equation 6 in Table H.3 was used. For the highest CEC category, Equation 5 was used. For the second step, these calculated values were adjusted by "eye balling the data" to agree with the data in Figures H.2-H.4. It is important to note that some of the look-up table categories did not have any actual observations, *e.g.*, pH <5 and CEC = 10 to 50 meq/100 g. For these categories, the regression analysis and the values in adjacent categories were used to assist in the K_d selection process.

Table H.4. Look-up table for estimated range of K_d values for strontium based on CEC and pH. [Tabulated values pertain to systems consisting of natural soils (as opposed to pure mineral phases), low ionic strength (< 0.1 M), low humic material concentrations (<5 mg/l), no organic chelates (such as EDTA), and oxidizing conditions.]

	CEC (meq/100 g)								
	3			3 - 10			10 - 50		
	pH			pH			pH		
K_d (ml/g)	< 5	5 - 8	8 - 10	< 5	5 - 8	8 - 10	< 5	5 - 8	8 - 10
Minimum	1	2	3	10	15	20	100	200	300
Maximum	40	60	120	150	200	300	1,500	1,600	1,700

Table H.5. Look-up table for estimated range of K_d values for strontium based on clay content and pH. [Tabulated values pertain to systems consisting of natural soils (as opposed to pure mineral phases), low ionic strength (< 0.1 M), low humic material concentrations (<5 mg/l), no organic chelates (such as EDTA), and oxidizing conditions.]

	Clay Content (wt.%)								
	< 4%			4 - 20%			20 - 60%		
	pH			pH			pH		
K_d (ml/g)	< 5	5 - 8	8 - 10	< 5	5 - 8	8 - 10	< 5	5 - 8	8 - 10
Minimum	1	2	3	10	15	20	100	200	300
Maximum	40	60	120	150	200	300	1,500	1,600	1,700

A second look-up table (Table H.5) was created from the first look-up table in which clay content replaced CEC as an independent variable. This second table was created because it is likely that clay content data will be more readily available for modelers than CEC data. To accomplish this, clay contents associated with the CEC values used to delineate the different categories were calculated using regression equations; Equation 11 was used for the high category (10 to 50 meq/100 g) and Equation 10 was used for the 2 lower CEC categories. The results of these calculations are presented in Table H.6. It should be noted that, by using either Equation 11 or 12, the calculated clay content at 15 meq/100 g of soil equaled 20 percent clay.

Table H.6. Calculations of clay contents using regression equations containing cation exchange capacity as a independent variable.

Equation[1]	Y-Intercept	Slope	CEC (meq/100 g)	Clay Content (%)
12	---	1.34	3	4
12	---	1.34	15	20
11	3.36	1.1.2	15	20
11	3.36	1.12	50	59
[1] Number of equation in Table H.3.				

H.3.0 K_d Data Set for Soils

Table H.7 lists the available K_d values identified for experiments conducted with only soils. The K_d values are listed with ancillary parameters that included clay content, pH, CEC, surface area, solution calcium concentrations, and solution strontium concentrations.

Table H.7. Strontium K_d data set for soils.

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] ppm	[Sr]	Background Solution	Soil ID	Reference [1], Comments
21	0.8	5.2	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
19	0.8	5.6	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
22	0.8	6.2	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
26	0.8	6.45	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
24	0.8	6.6	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
30	0.8	8.4	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
43	0.8	9.2	0.9	1.4	0	*	NaClO₄	Soil A	1, * = 4.4e2Bq/ml 85-Sr in 2.4x10⁻⁸ M SrCl₂
21.4	5		0.47				Groundwater		2
25	5		0.83				Groundwater		2, CEC was estimated by adding exch. Ca,Mg,K
12.7	5		0.39				Groundwater		2, GW = 7.4Ca, 1.7Mg, 2.2Na,5.6Cl, 18ppmSO4
7.9	5		0.46				Groundwater		2, Aquifer sediments
15.6	5		0.81				Groundwater		Chalk River Nat'l Lab, Ottawa, Canada
9.4	5		0.21				Groundwater		2, Described as sand texture
7.6	5		0.25				Groundwater		2, Assumed 5% clay, mean [clay] in sandy soils
6.4	5		0.24				Groundwater		2
7.7	5		0.26				Groundwater		2
28.1	5		0.76				Groundwater		2

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] ppm	[Sr]	Background Solution	Soil ID	Reference [1], Comments
7.63	5		0.26				Groundwater		2
11.4	5		0.41				Groundwater		2
20.1	5		0.44				Groundwater		2
13	5		0.25				Groundwater		2
9.8	5		0.29				Groundwater		2
11	5		0.22				Groundwater		2
13	5		0.39				Groundwater		2
7.8	5		0.2				Groundwater		2
3.8	5		0.1				Groundwater		2
3	5		0.1				Groundwater		2
2.5	5		0.13				Groundwater		2
4	10	4	5.5		0	1×10^{-8}M	0.01M NaCl	Puye soil-Na	3
15	10	5	5.5		0	1×10^{-8}M	0.01M NaCl	Puye soil-Na	3, Noncalcareous soils
21	10	6	5.5		0	1×10^{-8}M	0.01M NaCl	Puye soil-Na	3
24	10	7.4	5.5		0	1×10^{-8}M	0.01M NaCl	Puye soil-Na	3
3	10	3.6	5.5		400	1×10^{-8}M	0.01M CaCl	Puye soil-Ca	3
4.5	10	5.2	5.5		400	1×10^{-8}M	0.01M CaCl	Puye soil-Ca	3
5.2	10	6.8	5.5		400	1×10^{-8}M	0.01M CaCl	Puye soil-Ca	3
5.7	10	7.9	5.5		400	1×10^{-8}M	0.01M CaCl	Puye soil-Ca	3
3.5		5.2	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
4.6		5.6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4, Carbonate system
5.8		5.8	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
6.1		5.9	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m^2/g)	[Ca] ppm	[Sr]	Background Solution	Soil ID	Reference [1], Comments
8.3		6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
17		7.4	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
21		7.6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
27		7.8	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
47		8.4	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
81		9.1	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	4
19.1	4	7.66	10.4		129	100 µCi/l	Hanford Groundwater	cgs-1	5
21.5	6	7.87	5.9		58.5	100 µCi/l	Hanford Groundwater	trench-8	5, Groundwater pH = 8.3
23.2	5	8.17	4.57		35.1	100 µCi/l	Hanford Groundwater	tbs-1	5, Hanford, Richland, Washington surface and subsurface sediments
48.5		8.24	3			3.8×10^{-8}M	Yucca Groundwater	YM-22	6, Los Alamos, New Mexico
10,200		8.17	54			3.8×10^{-8}M	Yucca Groundwater	YM-38	6, Yucca Mountain tuff sediments
2,500		8.13	21			3.8×10^{-8}M	Yucca Groundwater	YM48	6, Approximate initial pH, final pH are presented
3,790		8.24	27			3.8×10^{-8}M	Yucca Groundwater	YM-49	6, Final pH 8.1- 8.5
3,820		8.24	27			3.8×10^{-8}M	Yucca Groundwater	YM-50	6, Sediments = 106-500 µm fractions
1.6	0.5	6.2	0.05			10×10^{-6}M	Groundwater	Sediments	7
2.6	3	6.2	0.3			10×10^{-6}M	Groundwater	Sediments	7, Added kaolinite to sand
3.4	5	6.2	0.5			10×10^{-6}M	Groundwater	Sediments	7, CEC estimated based on kaolinite = 10 meq/100 g
4.6	8	6.2	0.8			10×10^{-6}M	Groundwater	Sediments	7
6.7	13	6.2	1.3			10×10^{-6}M	Groundwater	Sediments	7
400	42.4	7.2	34		0		Water	Ringhold Soil	8, soil from Richland, Washington

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] ppm	[Sr]	Background Solution	Soil ID	Reference [1], Comments
135	26.9	8.3	13.6		0		Water	Bowdoin Soil	8, soil from Montana
600	33.5	6.5	26.3		0		Water	Hall soil	8, soil from Nebraska
70	3.5	8.3	5.8		0		Water	Composite Soil	8, soil from Hanford Site, Richland, Washington

[1] References: 1 = Ohnuki, 1994, 2 = Patterson and Spoel, 1981; 3 = Keren and O'Connor, 1983; 4 = Rhodes and Nelson, 1957; 5 = Serne *et al.*, 1993; 6 = Vine *et al.*, 1980; 7 = Lieser and Steinkopff, 1989; 8 = McHenry, 1958

H.4.0 K_d Data Set for Pure Mineral Phases and Soils

Table H.8 lists the available K_d values identified for experiments conducted with pure mineral phases as well as soils. The K_d values are listed with ancillary parameters that included clay content, pH, CEC, surface area, solution calcium concentrations, and solution strontium concentrations.

Table H.8. Strontium K_d data set for pure mineral phases and soils.

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
21	0.8	5.2	0.9	1.4	0	*	NaClO$_4$	Soil A	1, Ohnuki, 1994
19	0.8	5.6	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
22	0.8	6.2	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
26	0.8	6.45	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
24	0.8	6.6	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
30	0.8	8.4	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
43	0.8	9.2	0.9	1.4	0	*	NaClO$_4$	Soil A	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
0		5.5				*		Quartz	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
290		5.5	3.3	26.4	0	*		Kaolinite	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
140		5.5	3.6	43.9	0	*		Halloysite	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
17		5.5	0.6	1.4	0	*		Chlorite	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
37		5.5	1.9	2.2	0	*		Sericite	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
8		5.5	0.5	0.7	0	*		Oligoclase	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$
6		5.5	0.5		0	*		Hornblend	1, * = 4.4×10^2 Bq/ml 85-Sr in 2.4×10^{-8}M SrCl$_2$

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
16		5.5	0.7		0	*		Pyroxene	1, * = $4.4x10^2$ Bq/ml 85-Sr in $2.4x10^{-8}$M SrCl$_2$
110		5.5	8.5	19.3	0	*		MnO$_2$	1, * = $4.4x10^2$ Bq/ml 85-Sr in $2.4x10^{-8}$M SrCl$_2$
7.7		5.8			24	113 µCi/l	Groundwater	AA 45/1	2 Jackson and Inch, 1989
9.9		6.1			25	105 µCi/l	Groundwater	AA45/3	2, K_d = -.38Ca + 0.82. r2 = 0.19
12.6		6.1			23	105 µCi/l	Groundwater	AA45/4	2, Ca not important to Sr K_d
13.7		5.8			22	123 µCi/l	Groundwater	AA45/5	2
10.1		6			24	99 µCi/l	Groundwater	AA45/7	2
15.8		5.8			21	143 µCi/l	Groundwater	AA38/1	2
13.8		5.8			27	113 µCi/l	Groundwater	AA38/2	2
11		5.9			21	114 µCi/l	Groundwater	AA38/3	2
14.2		5.6			21	124 µCi/l	Groundwater	AA38/4	2
6		5.8			24	115 µCi/l	Groundwater	AA38/5	2
7.5		5.9			21	117 µCi/l	Groundwater	AA38/6	2
6.9		5.9			17	108 µCi/l	Groundwater	AA38/8	2
8.3		6.1			24	68 µCi/l	Groundwater	AA27/1	2
8		6.2			21	71 µCi/l	Groundwater	AA27/2	2
6.7		6.2			28	72 µCi/l	Groundwater	AA27/3	2
6.8		6.2				84 µCi/l	Groundwater	AA27/4	2
4.9		6.2			18	84 µCi/l	Groundwater	AA27/5	2
5.1		6.2			19	87 µCi/l	Groundwater	AA27/6	2
8.5		6.2			17	88 µCi/l	Groundwater	AA27/7	2
8.8		6.2			18	90 µCi/l	Groundwater	AA27/8	2
5.6		6.3			20	77 µCi/l	Groundwater	AA34/1	2
5.3		6.4			16	79 µCi/l	Groundwater	AA34/2	2
7.2		6.4			18	65 µCi/l	Groundwater	AA34/3	2
5.1		6.3			18	72 µCi/l	Groundwater	AA34/4	2
6.5		6.4			17	75 µCi/l	Groundwater	AA34/5	2

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m^2/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
6		6.2			14	79 µCi/l	Groundwater	AA34/6	2
6.5		6.2			15	107 µCi/l	Groundwater	AA34/7	2
7.6		6.2			17	107 µCi/l	Groundwater	AA34/8	2
21.4			0.47				Groundwater		3 Patterson and Spoel, 1981
25			0.83				Groundwater		3, CEC was approximated by adding exch. Ca,Mg,K
12.7			0.39				Groundwater		3, Groundwater =7.4 ppm Ca, 1.7 ppm Mg, 2.2 ppm Na, 5.6 ppm Cl, 18 ppm SO_4
7.9			0.46				Groundwater		3
15.6			0.81				Groundwater		3
9.4			0.21				Groundwater		3
7.6			0.25				Groundwater		3
6.4			0.24				Groundwater		3
7.7			0.26				Groundwater		3
28.1			0.76				Groundwater		3
7.63			0.26				Groundwater		3
11.4			0.41				Groundwater		3
20.1			0.44				Groundwater		3
13			0.25				Groundwater		3
9.8			0.29				Groundwater		3
11			0.22				Groundwater		3
13			0.39				Groundwater		3
7.8			0.2				Groundwater		3
3.8			0.1				Groundwater		3
3			0.1				Groundwater		3
2.5			0.13				Groundwater		3
4	10	4	5.5		0	$1x10^{-8}$M	.01M NaCl	Puye soil-Na	4
15	10	5	5.5		0	$1x10^{-8}$M	.01M NaCl		4, Noncalcareous soils

H.18

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m^2/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
21	10	6	5.5		0	1×10^{-8}M	.01M NaCl		4
24	10	7.4	5.5		0	1×10^{-8}M	.01M NaCl		4
3	10	3.6	5.5		400	1×10^{-8}M	.01M $CaCl_2$	Puye soil-Ca	4
4.5	10	5.2	5.5		400	1×10^{-8}M	.01M $CaCl_2$		4
5.2	10	6.8	5.5		400	1×10^{-8}M	.01M $CaCl_2$		4
5.7	10	7.9	5.5		400	1×10^{-8}M	.01M $CaCl_2$		4
7.2		3			0	0.1 ppm	2,000 ppm Na	Hanford Soil	5
12.7		5			0	0.1 ppm	2,000 ppm Na	Hanford Soil	5
14.9		7			0	0.1 ppm	2,000 ppm Na	Hanford Soil	5
12.9		9			0	0.1 ppm	2,000 ppm Na	Hanford Soil	5
25.1		11			0	0.1 ppm	2,000 ppm Na	Hanford Soil	5
40.6				0.98				C-27	6
48.6				0.96				C-27	6
35				0.88				C-97	6
39.2				0.8				C-55	6
25.2				0.73				C-81	6
16.4				0.39				C-62	6
10.3				0.36				C-71	6
8.2				0.32				C-85	6
7.6				0.25				C-77	6
7.8				0.51				MK-4	6
11.2				0.38				TK3	6
10.5				0.34				RK2	6
3.7				0.34				NK2	6
3.5		5.2	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
4.6		5.6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7

H.19

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m^2/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
5.8		5.8	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
6.1		5.9	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
8.3		6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
17		7.4	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
21		7.6	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
27		7.8	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
47		8.4	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
81		9.1	2		0	1×10^{-10}M	NaOH/HCl	Hanford soil	7
140	70	2.4		70	0	1×10^{-8}M	Water	Bentonite	8
160	70	2.4		70		1×10^{-8}M	Groundwater	Bentonite	8
1500	70	9.3		70	0	1×10^{-8}M	Water	Bentonite	8
1100	70	9.3		70		1×10^{-8}M	Groundwater	Bentonite	8
1800	10	6.1		130	0	1×10^{-8}M	Water	Takadate Loam	8, hydrohalloysite=10%, 70% silt
950	10	8		130		1×10^{-8}M	Groundwater	Takadate Loam	8, hydrohalloysite=10%, 70% silt
550	10	6.5		60	0	1×10^{-8}M	Water	Hachinohe Loam	8, hydrohalloysite = 10%, 90% silt
260	10	8.2		60		1×10^{-8}M	Groundwater	Hachinohe Loam	8, hydrohalloysite = 10%, 90% silt
19.1	4	7.66	10.4		129	100 µCi/l	Hanford Groundwater	cgs-1	9
21.5	6	7.87	5.9		58.5	100 µCi/l	Hanford Groundwater	trench-8	9, Groundwater pH = 8.3
23.2	5	8.17	4.57		35.1	100 µCi/l	Hanford Groundwater	tbs-1	9
48.5	0	8.24	3			3.8×10^{-8}M	Yucca Groundwater	YM-22	10, Los Alamos, New Mexico
10200	0	8.17	54			3.8×10^{-8}M	Yucca Groundwater	YM-38	10, Yucca Mt tuff sediments
2500	0	8.13	21			3.8×10^{-8}M	Yucca Groundwater	YM48	10, Approximate initial pH, final pH are presented
3790	0	8.24	27			3.8×10^{-8} M	Yucca Groundwater	YM-49	10, Final pH 8.1- 8.5

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
3820	0	8.24	27			3.8×10^{-8}M	Yucca Groundwater	YM-50	10, Sediments = 106-500 μm fractions
27000	0	8.4		31	10	3.8×10^{-8}M	Yucca Groundwater	JA-18	10
4850	0	8.63		31	50	3.8×10^{-8}M	Yucca Groundwater	JA-19	10
85	0	8.25		8	10	3.8×10^{-8}M	Yucca Groundwater	JA-32	10
17.7	0	8.5		8	50	3.8×10^{-8}M	Yucca Groundwater	JA-33	10
385	0	8.39		105	10	3.8×10^{-8}M	Yucca Groundwater	JA-37	10
149	0	8.45		105	50	3.8×10^{-8}M	Yucca Groundwater	JA-38	10
25000		12				10 nCi/ml		kaolinite	13
530		12				10 nCi/ml		chlorite	13
71,000		12				10 nCi/ml		FeOOH	13
1.6	0.5	6.2	0.05			10×10^{-6}M	Groundwater	Sediments	14
2.6	3	6.2	0.3			10×10^{-6}M	Groundwater	Sediments	14, Added Kaolinite to sand
3.4	5	6.2	0.5			10×10^{-6}M	Groundwater	Sediments	14, CEC estimated based on kaolinite = 10 meq/100 g
4.6	8	6.2	0.8			10×10^{-6}M	Groundwater	Sediments	14
6.7	13	6.2	1.3			10×10^{-6}M	Groundwater	Sediments	14
17,000			97			1×10^{-10}M		Ohya tuff	14, Akiba and Hashimoto, 1990
150			3.4			1×10^{-10}M		Pyrophyllite	14, log K_d = log CEC + constant: for trace [Sr]
780			2.4			1×10^{-10}M		Sandstone	14, pH not held constant, ranged from 6 to 9.
95			1.9			1×10^{-10}M		Shale	14, 1g solid:50ml sol'n,centrifuged,32-60mesh
440			1.9			1×10^{-10}M		Augite Andesite	14, CEC of Cs and K_d of Sr
39			1.2			1×10^{-10}M		Plagiorhyolite	14

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
380			0.75			1×10^{-10}M		Olivine Basalt	14
50			0.57			1×10^{-10}M		Vitric Massive Tuff	14
82			0.54			1×10^{-10}M		Inada granite	14
22			0.35			1×10^{-10}M		Rokko Granite	14
1.3			0.033			1×10^{-10}M		Limestone	14
2,000			2			1×10^{-10}M		Muscovite	14
140			0.93			1×10^{-10}M		Chlorite	14
40			0.36			1×10^{-10}M		Hedenbergite	14
20			0.33			1×10^{-10}M		Hornblende	14
71			0.11			1×10^{-10}M		Grossular	14
150			0.07			1×10^{-10}M		Microcline	14
0.92			0.067			1×10^{-10}M		Forsterite	14
14			0.034			1×10^{-10}M		K-Feldspar	14
30			0.032			1×10^{-10}M		Albite	14
3			0.022			1×10^{-10}M		Epidote	14
23			0.0098			1×10^{-10}M		Quartz	14
400	42.4	7.2	34		0		Water	Ringhold Soil	11, Soil from Richland WA
135	26.9	8.3	13.6		0		Water	Bowdoin Soil	11, from Montana
600	33.5	6.5	26.3		0		Water	Hall Soil	11, from Nebraska
70	3.5	8.3	5.8		0		Water	Composite Soil	11, from Hanford Site
2.4		4					Groundwater	Eolian Sand	12
4.7		5						Eolian Sand	12, Belgian soils
6		7						Eolian Sand	12, Composition of Groundwater was not given
2.3		4						Mol White Sand	12, Compared static vs. dynamic Kd
5.5		5						Mol White Sand	12
4.8		7						Mol White Sand	12

Sr K_d (ml/g)	Clay Content (%)	pH	CEC (meq/ 100 g)	Surface Area (m²/g)	[Ca] (ppm)	[Sr]	Background Solution	Soil ID	Reference[1] and Comments
2.6		4						Mol Lignitic Sand	12
5.3		5						Mol Lignitic Sand	12
7.2		7						Mol Lignitic Sand	12

[1] References: 1 = Ohnuki, 1994; 2 = Jackson and Inch ,1989; 3 =Patterson and Spoel ,1981; 4 = Keren and O'Connor, 1983; 5 Nelson, 1959; 6 = Inch and Killey, 1987; 7 = Rhodes and Nelson, 1957; 8 = Konishi *et al.*, 1988; 9 = Serne *et al.*, 1993; 10 = Vine *et al.*, 1980; 11 = McHenry, 1958;12 = Baetsle *et al.*, 1964; 13 = Ohnuki, 1991; 14 = Lieser and Steinkopff, 1989

H.5.0 References

Adeleye, S. A., P. G. Clay, and M. O. A. Oladipo. 1994. "Sorption of Caesium, Strontium and Europium Ions on Clay Minerals." *Journal of Materials Science,* 29:954-958.

Akiba, D., and H. Hashimoto. 1990. "Distribution Coefficient of Strontium on Variety of Minerals and Rocks." *Journal of Nuclear Science and Technology,* 27:275-279.

Ames, L., and D. Rai. 1978. *Radionuclide Interactions with Soil and Rock Media. Volume 1: Processes Influencing Radionuclide Mobility and Retention, Element Chemistry and Geochemistry, Conclusions and Evaluation.* PB-292 460, Pacific Northwest National Laboratory, Richland, Washington.

Baetsle, L. H., P. Dejonghe, W. Maes, E. S. Simpson, J. Souffriau, and P. Staner. 1964. *Underground Radionuclide Movement.* EURAEC-703, European Atomic Energy Commission, Vienna, Austria.

Cantrell, K., P. F. Martin, and J. E. Szecsody. 1994. "Clinoptilolite as an In-Situ Permeable Barrier to Strontium Migration in Ground Water." In *In-Situ Remediation: Scientific Basis for Current and Future Technologies. Part 2.,* G. W. Gee and N. Richard Wing (eds.). pp. 839-850. Battelle Press, Columbus, Ohio.

Cui, D., and R. E. Eriksen. 1995. "Reversibility of Strontium Sorption on Fracture Fillings." In *Scientific Basis for Nuclear Waste Management XVIII*, T. Murakami and R. C. Ewing (eds.), pp. 1045-1052. Material Research Society Symposium Proceedings, Volume 353, Materials Research Society, Pittsburgh, Pennsylvania.

Del Debbio, J. A. 1991. "Sorption of Strontium, Selenium, Cadmium, and Mercury in Soil." *Radiochimica Acta,* 52/53:181-186.

Faure, G., and J. L. Powell. 1972. *Strontium Isotope Geology.* Springer-Verlag, Berlin, Germany.

Inch, K. J., and R. W. D. Killey. 1987. "Surface Area and Radionuclide Sorption in Contaminated Aquifers." *Water Pollution Research Journal of Canada,* 22:85-98.

Jackson, R. E., and K. J. Inch. 1989. "The In-Situ Adsorption of ^{90}Sr in a Sand Aquifer at the Chalk River Nuclear Laboratories." *Journal of Contaminant Hydrology*, 4:27-50.

Keren, R., and G. A. O'Connor. 1983. "Strontium Adsorption by Noncalcareous Soils - Exchangeable Ions and Solution Composition Effects." *Soil Science,* 135:308-315.

Konishi, M., K. Yamamoto, T. Yanagi, and Y. Okajima. 1988. "Sorption Behavior of Cesium, Strontium and Americium Ions on Clay Materials." *Journal of Nuclear Science and Technology,* 25:929-933.

Lefevre, R., M. Sardin, and D. Schweich. 1993. "Migration of Strontium in Clayey and Calcareous Sandy Soil: Precipitation and Ion Exchange." *Journal of Contaminant Hydrology,* 13:215-229.

Lieser, K. H., B. Gleitsmann, and Th. Steinkopff. 1986. "Sorption of Trace Elements or Radionuclides in Natural Systems Containing Groundwater and Sediments." *Radiochimica Acta*, 40:33-37.

Lieser, K. H., and Th. Steinkopff. 1989. "Sorption Equilibria of Radionuclides or Trace Elements in Multicomponent Systems." *Radiochimica Acta,* 47:55-61.

McHenry, J. R. 1958. "Ion Exchange Properties of Strontium in a Calcareous Soil." *Soil Science Society of America, Proceedings,* 22:514-518.

Nelson, J. L. 1959. *Recent Studies at Hanford on Soil and Mineral Reactions in Waste Disposal.* HW-SA-2273, Westinghouse Hanford Company, Richland, Washington.

Hem, J. D. 1985. *Study and Interpretation of the Chemical Characteristics of Natural Water.* Water Supply Paper 2254. Distribution Branch, Text Products Section, U.S. Geological Survey, Alexandria, Virginia.

Neter, J. and W. Wasserman. 1974. *Applied Linear Statistical Models.* Richard D. Irwin, Inc., Homewood, Illinois.

Ohnuki, T. 1991. "Characteristics of Migration of [85]Sr and ^{137}Cs in Alkaline Solution Through Sandy Soil." *Material Research Society Proceedings,* 212:609-616.

Ohnuki, T. 1994. "Sorption Characteristics of Strontium on Sandy Soils and Their Components." *Radiochimica Acta,* 64:237-245.

Patterson, R. J., and T. Spoel. 1981. "Laboratory Measurements of the Strontium Distribution Coefficient for Sediments From a Shallow Sand Aquifer." *Water Resources Research,* 17:513-520.

Petersen, L. W., P. Moldrup, O. H. Jacobsen, and D. E. Rolston. 1996. "Relations Between Specific Surface Area and Soils Physical and Chemical Properties." *Soil Science*, 161:9-21.

Rhodes, D. W., and J. L. Nelson. 1957. *Disposal of Radioactive Liquid Wastes From the Uranium Recovery Plant.* HW-54721, Westinghouse Hanford Company, Richland, Washington.

Satmark, B., and Y. Albinsson. 1991. "Sorption of Fission Products on Colloids Made of Naturally Occurring Minerals and the Stability of these Colloids." *Radiochimica Acta*, 58/59:155-161.

Serne, R. J., J. L. Conca, V. L. LeGore, K. J. Cantrell, C. W. Lindenmeier, J. A. Campbell, J. E. Amonette, and M. I. Wood. 1993. *Solid-Waste Leach Characteristics and Contaminant-Sediment Interactions. Volume 1: Batch Leach and Adsorption Tests and Sediment Characterization.* PNL-8889, Pacific Northwest National Laboratory, Richland, Washington.

Serne, R. J., and V. L. LeGore. *Strontium-90 Adsorption-Desorption Properties and Sediment Characterization at the 100 N-Area.* PNL-10899, Pacific Northwest National Laboratory, Richland, Washington.

Sposito, G. 1984. *The Surface Chemistry of Soils.* Oxford University Press, New York, New York.

Strenge, D. L., and S. R. Peterson. 1989. *Chemical Databases for the Multimedia Environmental Pollutant Assessment System.* PNL-7145, Pacific Northwest National Laboratory, Richland, Washington.

Vine, E. N., R. D. Aguilar, B. P. Bayhurst, W. R. Daniels, S. J. DeVilliers, B. R. Erdal, F. O. Lawrence, S. Maestas, P. Q. Oliver, J. L. Thompson, and K. Wolfsberg. 1980. *Sorption-Desorption Studies on Tuff. II. A Continuation of Studies with Samples form Jackass Flats, Nevada and Initial Studies with Samples form Yucca Mountain, Nevada.* LA-8110-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.